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Bluff recession rates along the Lake Michigan shoreline in Illinois

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Bluff Recession Rates Along the Lake Michigan Shoreline in Illinois

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ABSTRACT

Using historical airphotos and maps, we measured amounts of bluff-top retreat at 300 locations along 30 km of the Lake Michigan shoreline from Wilmette to Waukegan, Illinois. For two time periods, 1872-1937 and 1937-1987, rates of retreat vary from 10 to 75 cm/yr between discrete segments of bluffs (defined by lithology) and between time periods for a given bluff segment. The average retreat rates for the entire area, however, do not vary significantly between the two time periods and are approximately 20-25 cm/yr. Mean and maximum lake levels and rainfall also do not vary significantly between the two periods, and thus local temporal variations in retreat rate cannot be attributed to these factors. The density of groins constructed does vary between time periods but shows no effect on retreat rates. Local rate variations correlate closely with lithologic variations of the glacial materials exposed in the bluff, which consist of clay tills and outwash silts, sands, and gravels. The temporally constant regional retreat rates and the regular shape of the local shoreline indicate that a uniform rate of retreat prevailed and that local variations in rates balance out through time to produce long-term parallel (in map view) bluff retreat in the area. This parallel retreat probably is controlled by the uniform retreat rate of the lithologically homogeneous shoreface in front of the bluff.

INTRODUCTION

Record high levels of Lake Michigan in the mid-1980's caused severe shoreline erosion in the highly developed areas from Chicago to Waukegan, Illinois (Fig. 1). Much of this shoreline consists of steep bluffs that locally have responded to high lake levels by retreating at accelerated rates; this provoked concerns about the safety of structures along the shoreline. In order to document temporal and spatial variations in bluff retreat rates in recent historical time (since 1872), we measured the amount and calculated the rate of bluff retreat along the Illinois shoreline between Wilmette and Waukegan (Fig. 1). We then relate these variations to temporal changes in lake level and precipitation and spatial changes in bluff lithology and construction of shore-protective works to determine which, if any, of these factors influence bluff retreat rates.

The bluffs consist of Pleistocene Wisconsinan glacial deposits. Lake-plain sediment from glacial Lake Chicago (Clark and Rudloff, 1990) assigned to the Equality Formation (Willman and Frye, 1970) locally overlies and is interspersed between tills of the Lake Border Morainic

System (Willman, 1971), a morphostratigraphic unit of the Wadsworth Member of the Wedron Formation (Frye et al., 1969). Although Clark and Rudloff (1990) show that the Wedron Member includes a variety of glaciolacustrine deposits as well as true tills, we designate these deposits as till for brevity. The Zion City Moraine, a silty clay till containing interbeds of glaciolacustrine silt, sand, and gravel, forms the bluffs from Waukegan to the Great Lakes Naval Training Center (Fig. 1). From the Naval Training Center to Lake Forest, the bluffs consist of lake-plain silts, sands, and gravels overlying 3-4 m of till exposed at the base of the bluff. The Highland Park Moraine, similar to the Zion City Moraine, is exposed from Lake Forest to Winnetka. Between Winnetka and Wilmette, the bluff is only 5-10 m high and consists of lake-plain silts and gravel interbeds overlying about 2 m of till exposed at the base of the bluff.

The bluffs are 5-25 m high and average about 17 m high. Slope angles are generally 25-35° but in some places are almost vertical. The bluffs support a thick cover of deciduous trees and associated underbrush. Perched ground water commonly seeps from the bluff face along contacts between layers of contrasting permeability. Most of the length of the bluff has some sort of engineered shore protection, but type and quality vary substantially.

Previous studies in the Great Lakes region focused primarily on the mechanisms of bluff retreat (e.g., Edil and Vallejo, 1977; Edil and Bosscher, 1988) and on rates of retreat (e.g., Carter, 1976; Kilgour et al., 1976; Quigley and Di Nardo, 1980). Little has been published on bluff recession along the Illinois shore. Berg and Collinson (1976) and Lineback (1974) used maps and airphotos to determine rates of bluff-top retreat along 21 profiles for periods as long as 100 yr or more and compared rates in different areas. Larsen (1973) modeled bluff recession as a function of shoreline retreat at 26 evenly spaced locations between Waukegan and Wilmette to estimate spatial and temporal rate changes. Jibson and others (1990) and Jibson and Staude (1991) introduced the procedure discussed herein and estimated retreat rates in the area.

The present study expands on this previous work by measuring bluff retreat at 100-m intervals along the 30 km of shoreline from Wilmette to Waukegan during a 115-yr time period and thus is the most comprehensive bluff-retreat study undertaken in this area. Our procedures are simple and can be applied to other coastal bluff areas if maps and (or) airphotos of appropriate age and scale are available. The resulting high density of measurements across a large area and over a long time period yields a much larger and more detailed data base than has previously been available in this or perhaps any area. These data enable new interpretations of the rates and processes of bluff retreat and the consequent economic effects. Our findings and interpretations address three fundamental questions: What are the rates of bluff retreat in the area? Do these rates vary in time and space? What factors control this temporal and spatial variation in retreat rates?

MEASURING BLUFF RECESSION AND CALCULATING RECESSION RATES

We divided the 30 km of bluffs from the north side of Wilmette harbor to the north side of the Great Lakes Naval Training Center into 300 segments, each 100 m long. Segments were defined by projecting perpendicular lines from a baseline bearing N. 20° W. and were numbered from south to north (Fig. 1).

We compared bluff positions from three data sources: 1:20,000-scale topographic maps made in 1872 by the U.S. Army Corps of Engineers (earliest maps at a usable scale), 1:14,400-scale airphotos taken in 1936 (earliest airphotos), and 1:14,400-scale airphotos taken in 1987 (most recent airphotos). The best method to document changes in bluff position is to measure the distance from the upper edge of the bluff to a reference feature. A recognizable feature on all data sources is the Chicago and Northwestern railroad grade, which roughly parallels the shoreline in the area. On the 1872 maps, we plotted the baseline, segmented bluff, and measured the distance perpendicular to the baseline from the upper bluff edge to the center of the railroad grade for each segment. On the airphotos, we used a zoom-transfer scope to trace the position of the bluff edge onto U.S. Geological Survey topographic base maps (Evanston, Highland Park, and Waukegan 7½' quadrangles) enlarged to 1:12,000 scale. We plotted the baseline on the maps, segmented the bluffs, and measured the distance to the railroad grade for each segment. Bluff recession at each segment was calculated by comparing the distances between each pair of data sources. Thus, we derived recession records for the 115-yr period from 1872 to 1987, the 65-yr period from 1872 to 1937, and the 50-yr period from 1937 to 1987.

Primary sources of location error include inherent airphoto distortion and imperfect registration of the map and airphoto on the zoom-transfer scope. We estimate that the combined location error from all sources for single features plotted from airphotos does not exceed 3 m; thus, distances measured between any two features are accurate within 6 m, and comparisons of two such distances are accurate within 12 m. Measurements directly from the 1872 maps are estimated to be accurate within 5 m; comparisons with measurements from airphotos are thus accurate within 11 m. Location errors are probably random; thus, they should have little net effect on regional averages calculated from the large data base.

AMOUNTS OF RECESSION AND RECESSION RATES

From 1872 to 1987 the average amount of recession for all bluff segments was 29 m; the maximum for any segment was 155 m. Average amounts of recession for the 1872-1937 and 1937-1987 periods were 20 m and 11 m, respectively; maximum amounts were 130 m and 85 m. These amounts of recession are large in view of the dense development along most of the shoreline. To compare bluff retreat in different time intervals, we divided the amounts of retreat by the durations of the respective time periods to obtain the annual retreat rate.

Figure 2 shows annual bluff retreat rates for the three time periods and locations of lithologic contacts. Significant spatial variation in retreat rates appears related to lithologic contrasts. In the 1872-1987 and 1872-1937 periods (Fig. 2A and 2B), retreat rates in the lake-plain deposits are much greater than the rates in the tills. Temporal variations are apparent between the 1872-1937 and 1937-1987 retreat rates (Fig. 2B and 2C). The 1872-1937 rates vary markedly between lithologic units, whereas the 1937-1987 rates are more uniformly distributed throughout the area.

Table 1 records mean recession rates for each time period and each lithologic unit and changes in mean rates between periods. Overall retreat rates for the entire area are 20-30 cm/yr. Rates for individual lithologic units, however, define a much broader range, from 10 to 75 cm/yr. For each time period, the spatial rate variation relates to the lithology exposed. For 1872-1987, the two reaches where lake-plain sediment is exposed (LP-S and LP-N) have almost identical retreat rates that are much higher than the rates in the two till areas (HP and ZC). The 1872-1937 data show a similar rate contrast between lithologic types. In 1937-1987, the two till areas have almost identical rates, but the two lake-plain areas differ markedly from the tills and from each other.

Figure 2D shows changes in retreat rates between the two time periods. Positive values indicate a rate increase from the early to the late period. The lithologic control is striking. The rate-change data in Table 1 show that the lake-plain bluffs had much higher retreat rates from 1872 to 1937 than from 1937 to 1987 and that the till bluffs had little change (ZC) or much higher rates (HP) in the later period. Interestingly, most local areas experienced large rate changes of as much as 120 percent, but the overall rate change for the entire area was a rather modest 27 percent decrease.

The bluffs from Wilmette to Winnetka (the southern lake-plain deposits) are much lower and have gentler slopes than the bluffs from Winnetka to Waukegan (the high bluff); therefore, separate retreat rates were calculated for the morphologically distinct high bluff (Table 1). Overall retreat rates for the high bluff vary only slightly between time intervals. The rate for 1872-1937 is 21.6 cm/yr; for 1937-1987 it is 24.2 cm/yr. This difference of roughly 10 percent is insignificant as compared to the range of possible error in the method.

In summary, the data show that average retreat rates along the entire high bluff are very similar for the two time periods, but that local rates vary considerably between lithologic units. For example, along the Highland Park Moraine, the retreat rate more than doubled from the early to the late period; just to the north along the northern lake-plain bluffs, the retreat rate was halved.

FACTORS AFFECTING RATE OF BLUFF RETREAT

What causes the observed spatial and temporal variation in retreat rates along the bluffs? In this section, we examine and analyze how temporal variation in lake level and precipitation and spatial variation in bluff lithology and shore-protective works affect bluff retreat rates.

Temporal Changes in Lake Level

Lake-level change commonly is considered the major factor controlling bluff retreat (e.g, Carter, 1976). High stands of Lake Michigan commonly last several years and have caused local increases in bluff retreat (Lineback, 1974; Berg and Collinson, 1976). We analyzed longer term lake-level fluctuations (National Oceanic and Atmospheric Administration, no date) to identify patterns that could relate to changes in retreat rates and found none. Over the two time intervals studied, we calculated average values of (1) mean annual lake levels and (2) maximum annual lake levels. Remarkably, differences in these averages between the two periods are negligible: 0.1 cm and 0.2 cm, respectively, over a total range of 160-165 cm. Because bluffs might be most sensitive to extreme conditions, we also determined maximum values for mean and maximum annual lake levels; differences between the two time intervals were only 0.7 and 1.2, cm, respectively.

This comparison of two consecutive time periods, 50 and 65 yr long, shows that mean lake level was stable over those durations and that extreme levels were virtually identical. Therefore, at this time scale, changes in bluff retreat rates cannot be attributed to lake-level fluctuations. This is not to say that changes in lake level do not affect retreat rates at any time scale, but rather that because lake level did not change between the observed time intervals, it could not affect retreat rates between those intervals. Lake level certainly changes over shorter (a few years) and longer (several centuries or millennia) durations, but the time periods examined are appropriate for long-term planning in human terms because useful lifetimes for most structures are 50-100 yr.

Temporal Changes in Precipitation

Mean annual precipitation can affect bluff stability in several ways. In addition to affecting lake levels, rainfall also affects local ground-water conditions and surface runoff. Comparison of mean annual precipitation for the two time periods shows a difference of only about 5 cm, or 6 percent. Comparison of maximum annual rainfall in those intervals shows a difference of only 3 cm, or 2 percent. Thus, as with lake levels, no significant differences in rainfall occurred between the two time periods, and changes in bluff retreat rates do not relate to changes in rainfall at that time scale.

Bluff Lithology

As discussed above, bluff lithology relates closely to spatial differences in retreat rates. Lake-plain deposits, primarily sands and silts, have greater retreat rates than tills in all time periods and areas but one, the south lake-plain area from 1937 to 1987. Sands and silts lack significant cohesive strength, which may render lake-plain bluffs more susceptible to wave attack during high lake levels or major storms and to sediment loss due to sheetwash and gullying during rainstorms (Lineback, 1974). Also, the sand and silt layers conduct ground water to the bluff face, where seeps are common. Interbedded clayey till layers create perched water tables and confine some permeable silt and sand layers causing buildup of high pore-water pressures; both the perched and confined ground-water conditions contribute to landsliding along the bluff (Hadley, 1976; Lineback, 1974; Mickelson et al., 1977; Edil and Bosscher, 1988). Our observations indicate that the northern lake-plain bluffs contain the greatest concentration of landslides in the area.

The fine-grained tills are older and have greater overall shear strength than the lake-plain deposits (DuMontelle et al., 1976). Although the tills probably resist wave attack more effectively than silts and sands, they also are susceptible to deep-seated landsliding. Landslides are abundant along the bluffs of the Highland Park Moraine and, when they occur, shift the location of the upper edge of the bluff by a large amount almost instantly.

If lower retreat rates in the till as compared to the lake-plain deposits were to persist, the till bluffs would become headlands and the lake-plain bluffs would recede to become reentrants: an irregular coastline would develop. Such is not the case. The southwestern Lake Michigan shoreline, reflecting the geometry of the local glacial deposits, is very regular and broadly arcuate (Fig. 1). Apparently, retreat rates in different lithologic units vary in time to produce parallel (in map view) bluff retreat on a regional scale. For example, the more than doubling of the retreat rate along the Highland Park Moraine between the early and late periods corresponds in time with substantial reductions in retreat rates in adjacent lake-plain bluffs (Table 1). The 115-yr observation period is too brief to unequivocally document this phenomenon, but the regular coastline strongly supports a model of long-term parallel bluff retreat in the area.

Shore-Protective Works

Beginning in the late 1920's, an ambitious groin-building program began along much of the shoreline. Groins are vertical barriers extending from the beach offshore designed to trap sediment moving along shore and thus to widen beaches and protect bluffs from wave attack. During most of the early period (1872-1937), few groins existed along the bluffs. By the late 1930's, many groins were in place, and groin construction continued into the 1950's. Thus, comparing retreat rates between the two periods should provide insight for evaluating the effectiveness of groins on retarding bluff recession.

We used data reported by Larsen (1973) and originally compiled by the Illinois Division of Waterways (1958) on the number and distribution of groins in the area built between 1872 and 1955. About 95 percent of these groins were built after 1920. Table 1 records the numbers of groins built by 1955 along each section of bluff and their density (number of groins per kilometer). The data show that groins have no consistent effect on bluff retreat rate. The area having the greatest groin density (ZC) had a negligible change in retreat rate. The area having the lowest groin density (LP-S) experienced an 80-percent *reduction* in retreat rate, while the rate along the Highland Park Moraine, which had twice the groin density, more than doubled. Along the high bluff, which contains 92 percent of the groins, the retreat rate actually increased slightly. Thus, construction of this first generation of groins neither enhanced nor degraded bluff stability in a consistent manner.

This analysis only examines the effects of the earliest generation of groins. In the past 30 years, additional groins of higher quality and other types of shore protection—sea walls, rip-rap, revetment, and offshore breakwaters—have been constructed. No data exist to systematically examine the effects of these other measures. However, the relatively constant regional rate of retreat throughout the area between early and late periods suggests that shoreline engineering to date has not affected bluff recession rates.

DISCUSSION AND CONCLUSIONS

Retreat rates from our study are similar to those from previous studies of this area (Larsen, 1973; Lineback, 1974; Berg and Collinson, 1976) and other parts of the west shore of Lake Michigan (Southwestern Wisconsin Regional Planning Commission, 1989). Published recession rates for other Great Lakes shorelines composed of similar lithologic units are significantly greater than our rates; long-term (100-150 yr) average rates of 50-280 cm/yr have been documented for several reaches of the Lake Erie shoreline (Carter, 1976; Kilgour et al., 1976; Quigley et al., 1977; Quigley and Di Nardo, 1980). Recession rates also are greater along coastal till bluffs in the British Isles: rates along part of the Northern Ireland coast are 21-84 cm/yr (McGreal, 1979), and rates in southern England are 25-510 cm/yr (Barton and Coles, 1984). Thus, although retreat rates in Illinois are significant, they are modest compared to rates in other geologically similar areas.

Our results regarding the influence of various factors on retreat rates appear at odds with some conclusions of previous studies as well as with intuition. Changes in bluff retreat rates commonly have been expected to correlate with fluctuations in lake level, and over brief time intervals (several years) they have been shown to do so (e.g., Berg and Collinson, 1976; Carter, 1976; Lineback, 1974; Quigley et al., 1977; Quigley and Di Nardo, 1980). Over time periods of several decades, however, the influence of lake level vanishes because mean and maximum levels have not varied over these longer periods. The absence of correlation between groin construction and retreat rates argues against the conventional wisdom at the time of their construction—that groins would produce wider beaches that would protect bluffs from wave attack. The ineffectiveness and even detrimental effects of groins on bluff stability have been documented more recently (Inman and Brush, 1973; Larsen, 1973; Mickelson et al., 1977). Although the early generation of groins did not decrease bluff retreat rates, other more recent protective measure might; however, longer observation periods are needed to determine their effectiveness.

Of the factors examined, only variation in bluff lithology correlates with changes in retreat rate. Over the 115-yr period, retreat rates of lake-plain bluffs are much greater than those of till bluffs (Table 1). Retreat rates in all units except the Zion City Moraine vary substantially between early and late intervals; rates in lake-plain bluffs decrease, and rates in the Highland Park Moraine increase.

The minor changes in the regional retreat rates between the two time periods and the fairly linear, regular shape of the southern Lake Michigan shoreline both indicate that spatial and temporal changes in retreat rates balance out over time periods of several decades to centuries and that a uniform regional rate of retreat prevails. For the last 115 yr, that retreat rate is about 20-25 cm/yr, a significant amount both in human and geological terms. Although bluff segments composed of materials more susceptible to erosion and landsliding than adjacent segments will experience anomalously high rates of retreat for limited periods of time, the data indicate that rates in such areas will eventually decrease and allow adjacent segments to "catch up". Although the mechanism by which this occurs is uncertain, we surmise that the long-term regional bluff retreat rate is controlled by the rate of erosion and retreat of the shoreface in front of the bluff. The lithologic variation that causes localized differences in bluff retreat rates is confined to the upper part of the bluff. Throughout the area, the base of the bluff, the beach platform, and the shoreface all consist of hard clay till, covered in places by a thin veneer of sand and gravel. We can reasonably infer that a shoreface having essentially uniform lithology and physical properties erodes and retreats at a uniform rate throughout the area. Localized episodes of rapid bluff recession widen the beach platform and thus increase the distance from the base of the bluff to the shoreface, which does not necessarily react by eroding more quickly. In such areas, waves will break farther from the bluff base, and wave energy will be dissipated before reaching the base of the bluff. This effectively retards bluff recession until the shoreface retreats closer to the bluff. Thus, the uniform lithology and erosion rate of the shoreface could effectively damp excessive bluff-retreat in any given location and therefore constrain the geometry of the shoreline to its fairly linear shape.

For the most recent period of observation, 1937-1987, retreat rates along the till bluffs are about the same as the long-term regional average. Retreat rates in the northern lake-plain deposits are much greater than the regional average but are lower than those for the 1872-1937 interval; this decrease in retreat rate might be expected to continue if rate changes balance out through time. Rates for the southern lake-plain bluffs are much lower for the late time interval as compared to the early time interval. Retreat rates there might be expected eventually to increase toward the regional average unless shore-protective works maintain the low rate.

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TABLE 1. BLUFF RECESSION DATA

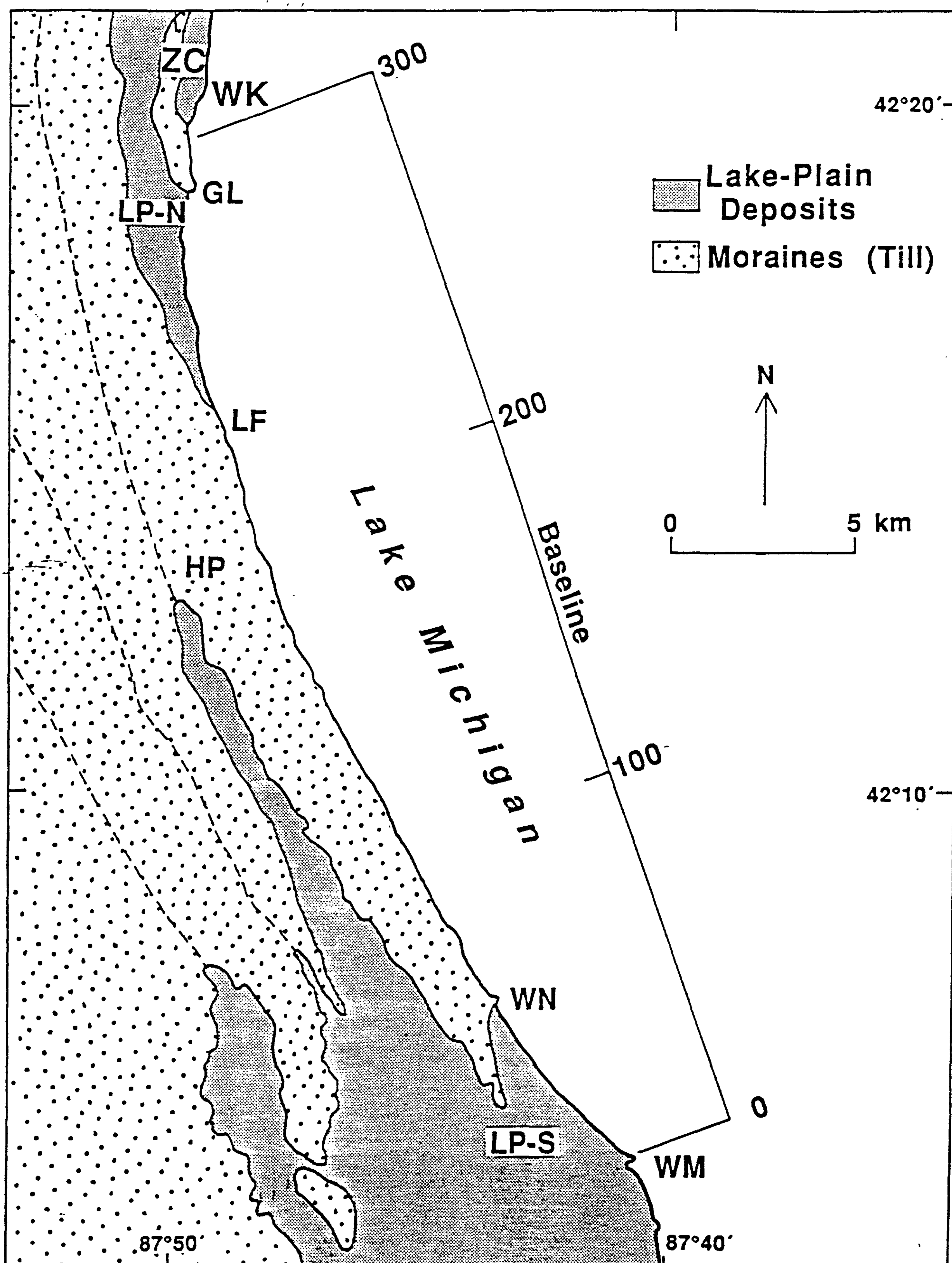
UNIT (segments)	RECESSION RATE 1872-1987 (cm/yr)	1872-1937 (cm/yr)	1937-1987 (cm/yr)	RATE CHANGE (cm/yr)	(%)	GROINS NUMBER	DENSITY (#/km)
LP-S (1-52)	46.8	73.2	12.7	-60.5	-82.7	9	1.7
HP (53-233)	13.2	10.2	22.6	12.4	121.6	64	3.5
LP-N (234-284)	45.8	59.2	30.4	-28.8	-48.6	26	5.1
ZC (285-300)	22.0	24.6	22.0	-2.6	-10.6	12	7.5
TOTAL BLUFF (1-300)	25.4	30.5	22.3	-8.2	26.9	111	3.7
HIGH BLUFF (53-300)	20.9	21.6	24.2	2.6	12.0	102	4.1

Note: Unit refers to lithologic unit: LP-S, south exposure of lake-plain deposits; HP, Highland Park Moraine; LP-N, northern exposure of lake-plain deposits; ZC, Zion City Moraine.

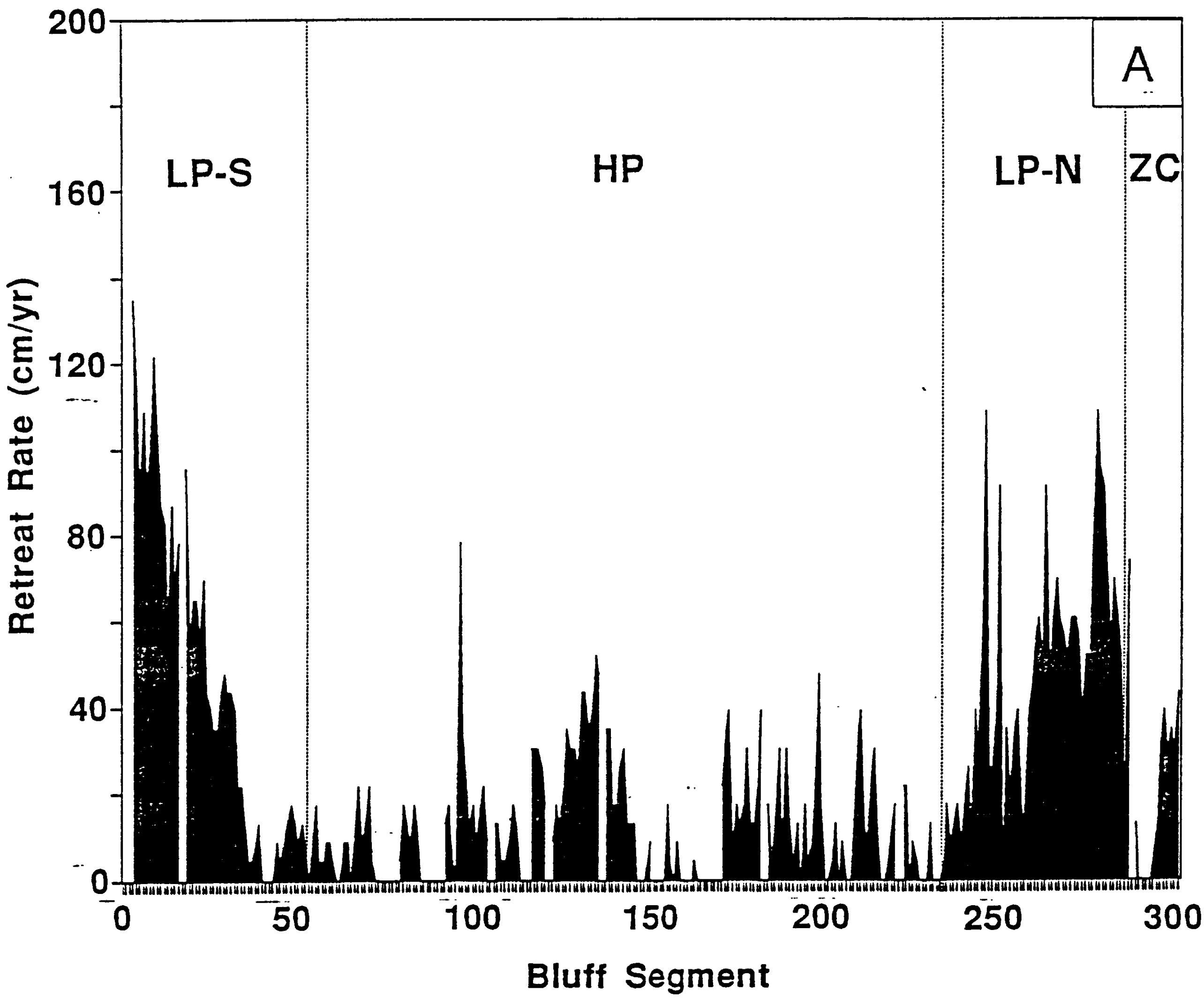
FIGURE CAPTIONS

Figure 1. Map showing the surficial geology of the study area (generalized from Willman and Lineback, 1970). Baseline shows bluff segment numbers. Geologic units: LP-N, northern exposure of lake-plain deposits; LP-S, southern exposure of lake-plain deposits; HP, Highland Park Moraine; ZC, Zion City Moraine. Dashed contacts separate distinct moraines. Cities are: WK, Waukegan; GL, Great Lakes Navel Training Center; LK, Lake Forest; WN, Winnetka, WM, Wilmette.

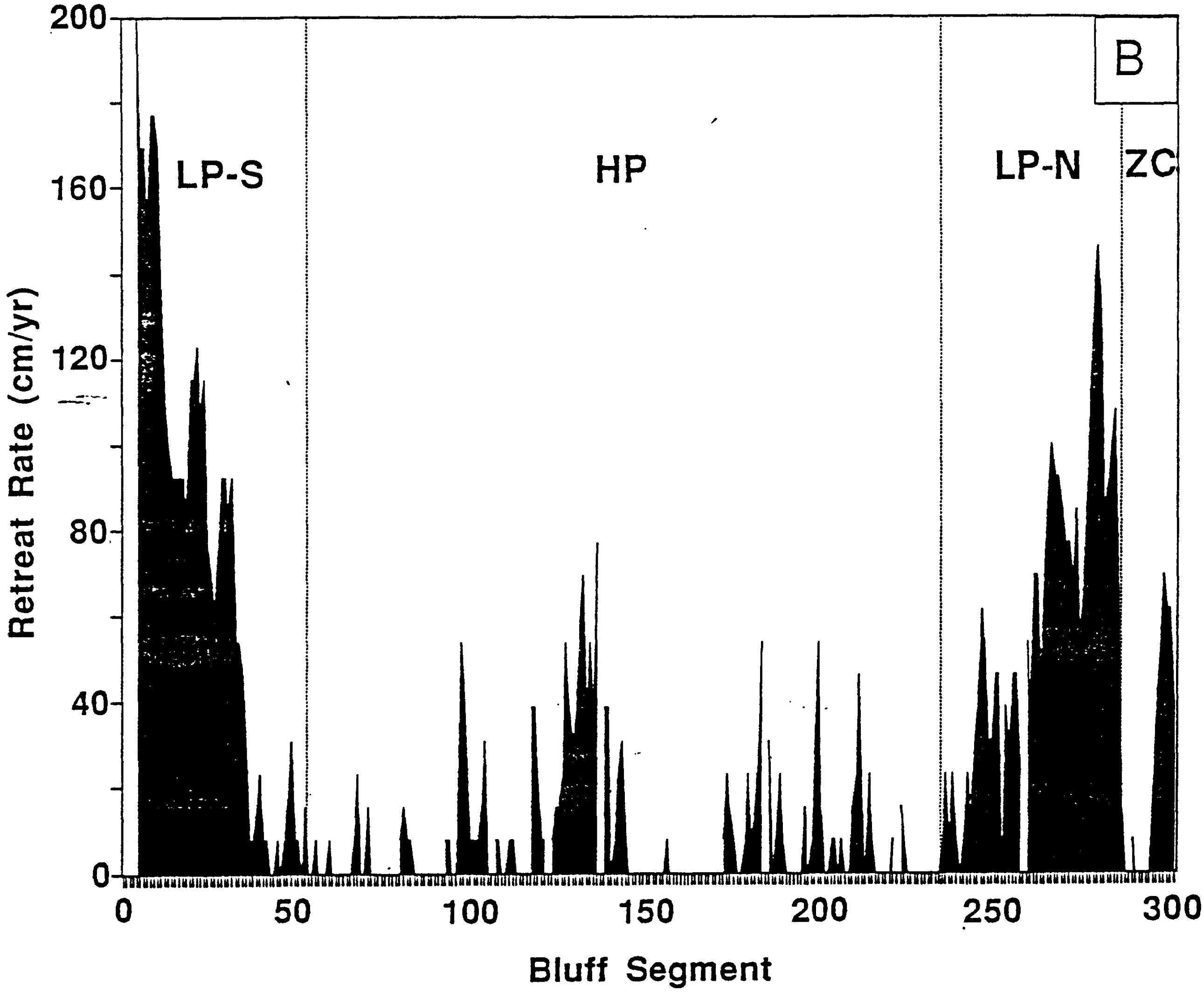
Figure 2. Annual rates and changes in rates of bluff retreat between Wilmette and Waukegan. A, retreat rates for 1872-1987; B, retreat rates for 1872-1937; C, retreat rates for 1937-1987; D, changes in retreat rates between 1872-1937 and 1937-1987 (positive values where rate is greater in the later period). Vertical dashed lines show locations of geologic contacts; abbreviations as in Figure 1.



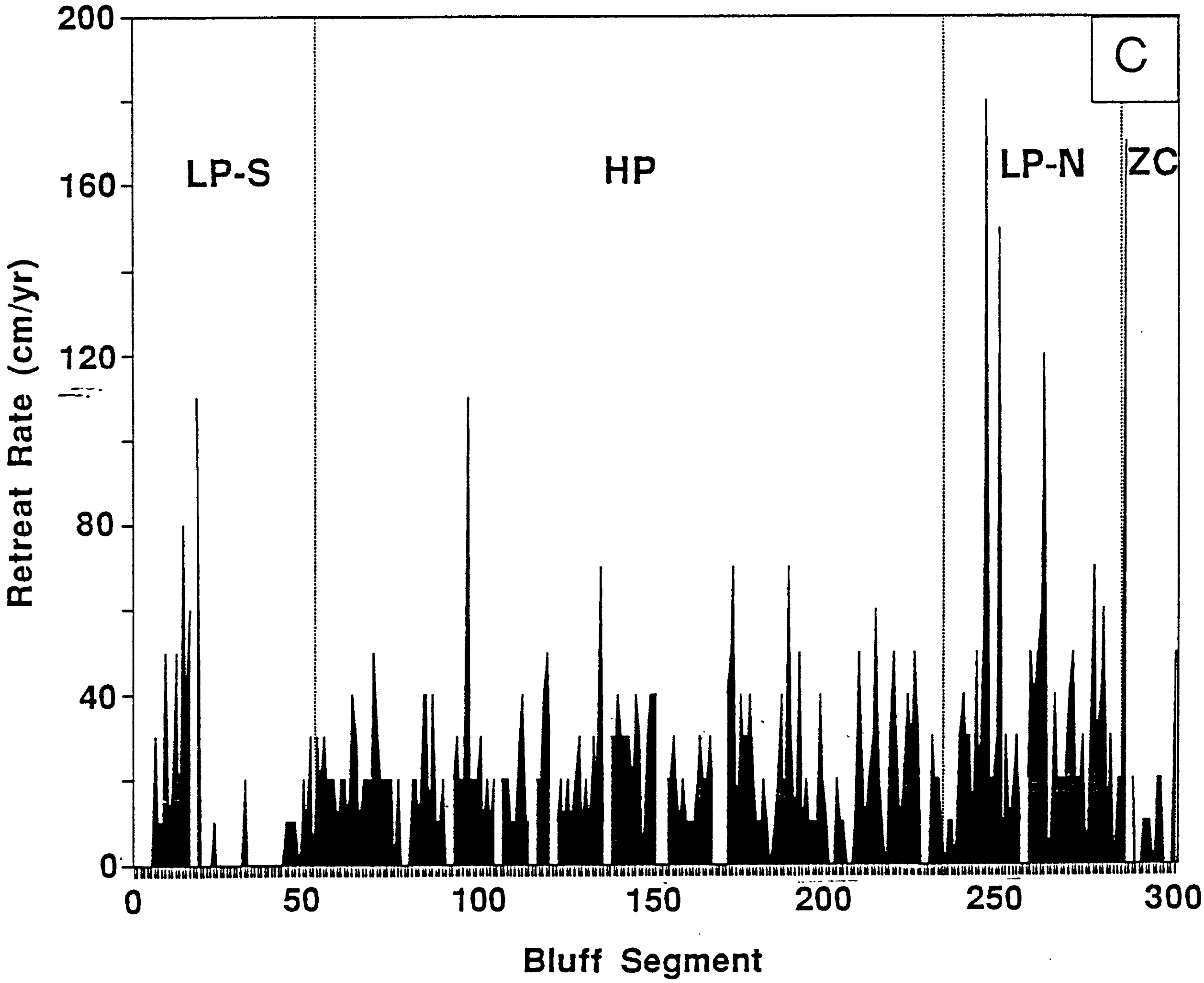
Jibson, Figure 1



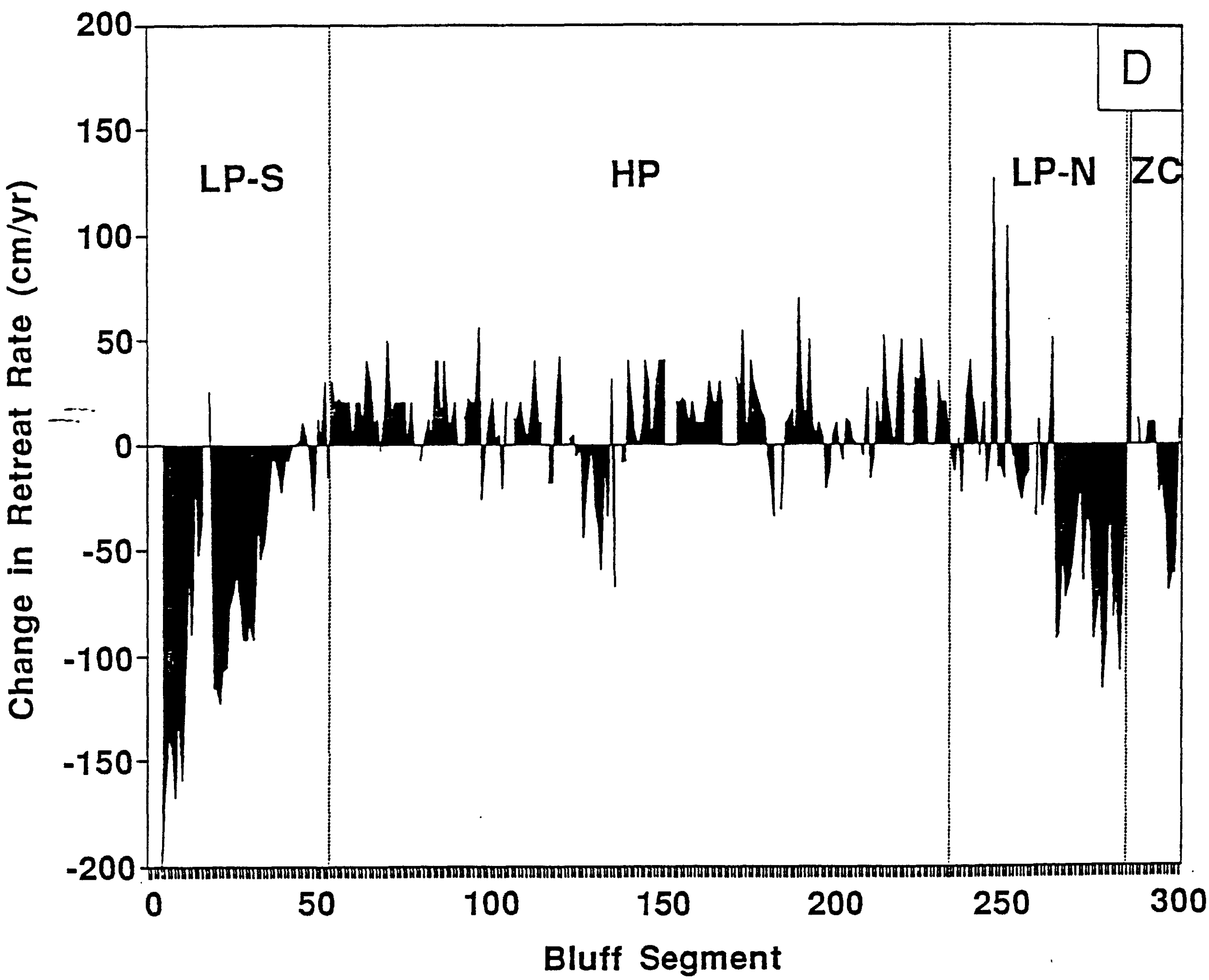
Jibson, Figure 2A



Jibson, Figure 2B



Jibson, Figure 2C



Jibson, Figure 2D